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THESIS

AN INVESTIGATION OF THE APAIR ACOUSTIC
DETECTION MODEL

by

Craig W. Goodman

September 1989

Thesis Advisor:

R. N. Forrest

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION UNCLASSIFIED			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED		
2b DECLASSIFICATION/DOWNGRADING SCHEDULE			5 MONITORING ORGANIZATION REPORT NUMBER(S)		
4 PERFORMING ORGANIZATION REPORT NUMBER(S)			5 MONITORING ORGANIZATION REPORT NUMBER(S)		
6a NAME OF PERFORMING ORGANIZATION NAVAL POSTGRADUATE SCHOOL		6b OFFICE SYMBOL (if applicable) 55		7a NAME OF MONITORING ORGANIZATION NAVAL POSTGRADUATE SCHOOL	
6c ADDRESS (City, State, and ZIP Code) MONTEREY, CALIFORNIA 93943-5000		7b ADDRESS (City, State, and ZIP Code) MONTEREY, CALIFORNIA 93943-5000			
8a NAME OF FUNDING, SPONSORING ORGANIZATION		8b OFFICE SYMBOL (if applicable)		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c ADDRESS (City, State, and ZIP Code)		10 SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO		PROJECT NO	TASK NO
					WORK UNIT ACCESSION NO
11 TITLE (Include Security Classification) AN INVESTIGATION OF THE APAIR ACOUSTIC DETECTION MODEL					
12 PERSONAL AUTHOR(S) GOODMAN, CRAIG W.					
13 MASTER'S THESIS		14 TIME COVERED FROM TO		15 DATE OF REPORT (Year, Month, Day) SEPTEMBER 1989	
				16 PAGE COUNT 51	
17 SUPPLEMENTARY NOTES: THE VIEW'S EXPRESSED IN THIS THESIS ARE THOSE OF THE AUTHOR AND DO NOT REFLECT THE OFFICIAL POLICY OR POSITION OF THE DEPARTMENT OF DEFENSE OR THE U.S. GOVERNMENT.					
18 COSAT CODES			19 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB GROUP	APAIR, LAMBDA-SIGMA		
20 ABSTRACT (Continue on reverse if necessary and identify by block number) THE SUBJECT OF THIS THESIS IS AN INVESTIGATION OF THE EFFECT OF USING THE LAMBDA-SIGMA JUMP PROCESS IN THE ACOUSTIC DETECTION COMPONENT OF APAIR. A COMPUTER SIMULATION WAS DEVELOPED WHICH IS SIMILAR TO THE SONOBUOY FIELD VERSUS SUBMARINE ENGAGEMENT MODEL FOUND IN APAIR, THE NAVY'S GENERAL ASW MODEL. THIS SIMULATION WAS THEN MODIFIED TO INCORPORATE THE LAMBDA-SIGMA JUMP PROCESS AND THE EFFECT OF THIS MODIFICATION IS DISCUSSED. IN ORDER TO CHECK THE STRUCTURAL VALIDITY OF THE SIMULATION MODELS, RESULTS THAT WERE OBTAINED BY USING THEM ARE COMPARED TO RESULTS THAT WERE OBTAINED BY USING AN ANALYTICAL MODEL CALLED THE RANDOM SEARCH MODEL.					
21 DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT <input type="checkbox"/> DTIC USERS			22 ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED		
23 NAME OF RESPONSIBLE INDIVIDUAL R.N. FORREST			24b TELEPHONE (include Area Code) (408) 646-2653		25c OFFICE SYMBOL 55Fo

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An Investigation of the APAIR
Acoustic Detection Model

by

Craig W. Goodman
Lieutenant, United States Naval Reserve
B.A., Humboldt State University, 1981

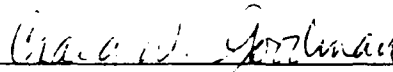
Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

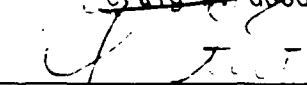
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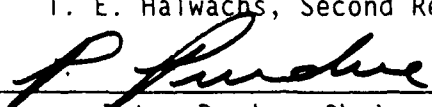
Author:


Craig W. Goodman

Approved by:


R. N. Forrest, Thesis Advisor


T. E. Halwachs, Second Reader


Peter Purdue, Chairman
Department of Operations Research

ABSTRACT

The subject of this thesis is an investigation of the effect of using the lambda-sigma jump process in the acoustic detection component of APAIR. A computer simulation was developed which is similar to the sonobuoy field versus submarine engagement model found in APAIR, the Navy's general ASW model. This simulation was then modified to incorporate the lambda-sigma jump process and the effect of this modification is discussed. In order to check the structural validity of the simulation models, results that were obtained by using them are compared to results that were obtained by using an analytical model called the random search model.



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I. INTRODUCTION

The number of sonobuoys needed to detect a submarine with a given probability can be estimated using a computer simulation. Various passive acoustic detection models that have been developed over the years can be used to form the basis of this simulation. One of these detection models is the stochastic signal excess model that is part of the sonobuoy field versus submarine section of APAIR, the Navy's general air ASW model. Another detection model that has been extensively used is one that incorporates a lambda-sigma jump process.

The purpose of this thesis is to investigate the effect of using the lambda-sigma jump process in the passive acoustic detection component of APAIR. To do this, a computer simulation, called Model A, was developed that incorporates the detection model found in the APAIR model. Model A was then modified by incorporating the lambda-sigma jump process in order to obtain a second computer simulation, called Model B. This modification was done in order to determine if that change would affect the estimate of the number of sonobuoys required to gain a detection with a given probability.

Chapter 2 provides a description of the two simulation models. Data generated by the two simulation models are compared in Chapter 3 with data obtained using an analytical model called the random search model. This was done in order to provide a check on the simulation's structural validity.

II. THE MODELS

Three models are discussed in this chapter. The first two are simulation models that are based on a stochastic signal excess acoustic detection model. The first model is called Model A and the second model is called Model B. The third is an analytical model called the random search model.

A. MODEL A

Model A is based on the following assumptions: At the start of a search, all the sonobuoys are in the water and operating and the submarine is in a submarine probability area, or SPA. The size of the SPA is 4900 nm^2 and it is assumed to be square in shape. The submarine's initial location is uniformly distributed over the SPA, its speed is constant at 5 kts, its course is constant and is equally likely to have any value between 0 and 360 degrees and its depth is 400 feet. The sonobuoy's receiver depth is 400 ft.

The environmental data for the model, such as propagation loss and ambient noise, are based on an area in the northwest part of the pacific ocean. Since some of the sonobuoys that are currently in use or are being developed may not have the ability to achieve convergence zone detections, it is assumed that detection can only be made out to a maximum of 10 nm in order to eliminate the possibility of this type of detection.

Signal excess is the difference between the signal-to-noise ratio in decibels and the detection threshold. If the signal excess is greater than or equal to zero, then the probability of detection is greater than or equal to a minimum acceptable value for a single observation. In this thesis, the minimum acceptable value is .5 and recognition differential is the term that is used to refer to detection threshold. For the model and for any time t , signal excess is a random variable that is defined as follows:

$$(1) \quad X_{SE}(t) = SE(t) + X(t).$$

In equation 1, $X_{SE}(t)$ is the signal excess, $SE(t)$ is the mean of the signal excess and $X(t)$ is a random variable that determines the stochastic character of the signal excess. Since $SE(t)$ is the mean of $X_{SE}(t)$, the mean of $X(t)$ is equal to zero and the standard deviation of $X(t)$ is equal to the standard deviation of $X_{SE}(t)$. The signal excess can also be defined as follows:

$$(2) \quad X_{SE}(t) = X_{SL}(t) - X_{TL}(t) - (X_{NL}(t) - X_{DI}(t)) - X_{RD}(t).$$

The subscripts have the following meaning: SE indicates signal excess, SL indicates the target's source level, TL indicates transmission loss, NL indicates noise level, DI indicates directivity index and RD indicates recognition differential. It is usually assumed that all the random variables on the right hand side of Equation 2 are normally distributed and statistically independent and thus $X_{SE}(t)$ is normally distributed and has a variance equal to the sum of the variances of the random variables on the right hand side.

The expected value of $X_{SE}(t)$ as defined by (2) is:

$$(3) \quad SE = SL - TL - (NL - DI) - RD$$

which can be interpreted as the passive sonar equation. The passive sonar equation represented by (3) can also be written in terms of the figure of merit, or FOM, as:

$$(4) \quad SE = FOM - TL$$

where

$$(5) \quad FOM = SL - (NL - DI) - RD$$

(see appendix A for a discussion of the passive sonar equation). The detection model that is the basis for the computer simulation is similar to the one used in a model developed by Vitro called RADS, an acronym for Rapid Acoustic Detection Simulation [Ref. 1]. The RADS detection model in turn, is similar to the sonobuoy field versus submarine acoustic detection model used in the APAIR model, the Navy's general air ASW engagement model. RADS was developed to specifically simulate a sonobuoy field's detection capability. Faster results can be obtained by using RADS as opposed to APAIR when one is interested only in sonobuoy field detection capability. Unlike the RADS model, Model A does not take into account aircraft motion and only simulates the target and the sonobuoy field. Also, it is not capable of simulating a transiting battle group performing barrier operations against a submarine. However, like RADS it is a monte carlo simulation of a sonobuoy field containing a single submarine.

In Model A, a submarine is treated as a point sound source which is not aspect dependent. Up to three separate source frequencies may be

specified at three separate source levels. The source levels which are determined off-line by the user, depend on the submarine type, speed, depth, and the operating conditions. For this thesis, only one frequency was used.

The simulation run time or game time is user controlled. For this thesis, it was 1200 minutes. This value was chosen since, for a submarine travelling at a constant speed of 5 knots, the maximum time the submarine can remain within a 4900 nm^2 square sonobuoy field is approximately 1200 minutes. The sonobuoys are placed in the search area such that there is equal spacing between each of the buoys and between the outer buoys and the edge of the SPA. It is assumed that all the sonobuoys operate for the entire 1200 minute run time.

The sonobuoy and acoustic processor characteristics are controlled by the user by inputting RD, and DI.

The primary features of the ocean acoustic environment which influence passive sonobuoys are ambient noise and transmission loss. These parameters are supplied by the user as part of the input data set. Three values of ambient noise can be input, one for each source frequency. Transmission loss is input in the form of tables, one table for each source frequency. The table consists of transmission loss in dB for every one-half nautical mile increment out to a user controlled maximum limit.

The detection process is simulated by computing the signal excess for each source frequency at each sonobuoy during every time step in the simulation. The time step increment is controlled by the user and remains constant. At each time step of the simulation, the signal excess for each

source frequency is determined as follows: First, the range between each sonobuoy and the submarine is computed. Based on this range, an interpolated value of transmission loss is calculated. Then, the signal excess is determined by using (1) where:

$$(6) \quad SE(t) = SL - NL - TL(t) - RD + DI$$

and:

$$(7) \quad X(t) = X_1 + X_2(t) + X_3.$$

This model simulates signal excess fluctuation by separating the total fluctuation into three individual and independent components: (1) long term or day to day fluctuation; (2) short term or minute to minute fluctuation; and (3) buoy to buoy fluctuation.

Long term fluctuation is caused by variation between operators, variation between average source levels of a particular submarine type and variation in ocean acoustic conditions caused by seasonal changes and day to day changes [Ref. 2]. X_1 represents the long term fluctuation and is a random variable whose values are determined by drawing from a normal distribution with a mean of zero and a user supplied standard deviation. Once the value of X_1 is obtained at the beginning of the simulation it remains constant for a full replication and the same value is used for every signal excess calculation at every sonobuoy. This implies that the model assumes complete dependence of the sonobuoys with respect to long term fluctuation.

Short term fluctuation is caused by changes in target aspect, changes in operator alertness, and variations in ocean acoustic conditions caused by shipping traffic and wind [Ref. 2]. $X_2(t)$ represents the short term

fluctuation. It is a random variable whose value is determined several times during a replication. The standard deviation and sampling interval or time between random draws of $X_2(t)$ are controlled by the user. At each sampling interval, a random draw is made from a normal distribution with a mean of zero and a user supplied standard deviation. The sampling interval of random draws of $X_2(t)$ was set at 30 minutes for this thesis [Ref. 3]. The values used in the signal excess equation for $X_2(t)$ are interpolated values between the values determined by successive draws of $X_2(t)$. Just as with X_1 , the same value for $X_2(t)$ is used to compute signal excess at every sonobuoy. Again, this implies complete dependence between sonobuoys for short term fluctuation.

The final term X_3 represents buoy to buoy fluctuation. This type of fluctuation could be caused by variations in the manufacturing process of the sonobuoys. At the beginning of each replication, a random draw is made for each sonobuoy from a normal distribution with a mean of zero and a user supplied standard deviation. This X_3 value is determined separately for each sonobuoy and is held constant for an entire replication. Once the three separate fluctuation terms are computed they are combined to form $X(t)$ and added to the sonar equation to obtain a signal excess value.

As stated earlier, the user must input values for the standard deviation of the random variables X_1 , $X_2(t)$, and X_3 . These values are not readily available.

A sensitivity analysis was conducted on these standard deviation terms, to determine if varying their values would have a significant effect on the probability of detection by using the following assumptions: (1) the standard deviation of signal excess is 8 dB [Ref. 4]; and (2) the individual standard deviations can be varied subject to:

$$(8) \quad \sigma_{SE} = \sqrt{\sigma_L^2 + \sigma_S^2 + \sigma_B^2}.$$

Where σ_{SE} is the standard deviation of signal excess, σ_L is the standard deviation of the long term fluctuation, σ_S is the standard deviation of the short term fluctuation and σ_B is the standard deviation of the buoy to buoy fluctuation.

The signal excess based on a standard integration time is computed at each time step. Detection occurs on the time step if a moving time average of the signal excess is above one of a set of user controlled signal excess decrements. These decrements account for the increase in RD at the initial time steps that result from integration times less than the standard integration time. The moving average is $(S_j + S_{j-1} + \dots + S_{j-k+1})/k$ where $j = 1, 2, 3, \dots$ is the time step index and $k = 1, 2, 3, \dots, j$, if $j < M$ and $k = M$ if $j \geq M$ where M is the number of samples in the standard integration time. The signal excess decrements are input in the form of a table of values $DEC(i)$.

For every sonobuoy and frequency, detection will occur when one of the following expressions is satisfied:

$$S_1 \geq \text{DEC}(1)$$

$$(S_1 + S_2)/2 \geq \text{DEC}(2)$$

.

.

.

$$(S_1 + S_2 + \dots + S_M)/M \geq \text{DEC}(M).$$

An example of a DEC table for $M = 5$ is as follows:

$$\text{DEC}(1) = 3.5$$

$$\text{DEC}(2) = 2.5$$

$$\text{DEC}(3) = 1.5$$

$$\text{DEC}(4) = 0.5$$

$$\text{DEC}(5) = 0.0.$$

This process of time integration of an acoustic signal is used in a model described by Forrest [Ref. 2]. Also, a continuous time model is described by McCabe and Belkin [Ref. 5]. It can be seen from this table that if the initial signal excess sample is 4 dB a detection will occur at the initial time step. If the initial sample is 3.2 dB and the second sample is 2.2 dB, neither sample is sufficient to make a detection. However, the time average of 2.7 dB is sufficient to make a detection based on the DEC(2) value of 2.5 dB. This simulates the decrease in the detection threshold with increasing integration time. The DEC values were obtained using a detection model described by Forrest [Ref. 2:pp. 27-29].

In this model, the probability of false alarm and the probability of detection can be defined as:

$$(9) \quad p_f = \Phi(-v^*)$$

and:

$$(10) \quad p_d = \Phi(-v^* + d^{1/2})$$

where p_f represents the probability of false alarm, p_d represents the probability of detection, Φ symbolizes the standard normal cumulative distribution function, v^* is a threshold value and d is the detection index. The detection index is defined as:

$$(11) \quad d = t(BW)(S/N)^2$$

where t represents time, BW represents bandwidth, and S/N represents the signal-to-noise ratio. Since detection threshold is defined as:

$$(12) \quad DT = 10 \log(S/N)$$

by using equation (11), equation (12) can be rewritten as:

$$(13) \quad DT = 5 \log(d/t(BW)).$$

Assuming a p_f of 0.001 and a p_d of 0.500 and using equations (9) and (10) the detection index, d , is computed to be equal to 9.551. Since p_d is 0.500, RD can be used vice DT. Assuming a BW of 1 Hz, a solution for RD can be obtained for various values of t . For this thesis, the integration time and the signal excess sampling interval were 12 minutes and two minutes respectively. Table 2.1 shows the values of RD for the various values of t . These 6 RD values were then used for the signal excess decrement values in the simulation.

Table: 2.1
RD values for corresponding
values of t

t	RD
2.0	3.395
4.0	1.890
6.0	1.010
8.0	0.385
10.0	-0.100
12.0	-0.496

Either a one, two, or three-source frequency (line) detection may be specified by the user. If, for example, a two-line detection is required, then one sonobuoy must be in contact on two frequencies in order for a detection to occur. One frequency held by one sonobuoy and another held by a second sonobuoy does not constitute a two-line detection. As noted above, only one frequency was used and therefore a one-line detection was specified.

B. MODEL B

A second simulation model called Model B was obtained by modifying the way Model A calculates $X(t)$. Model B uses a lambda-sigma jump process to calculate $X(t)$. For a description of the lambda-sigma jump model see Reference 5. This modification was made in order to determine if the method by which the two simulation models calculate $X(t)$ would have a significant effect on the models estimate of the number of sonobuoys

required to gain a detection with a given probability. The standard deviation of $X(t)$, for Model B, was assumed to be 8 dB and the mean time between jumps was 30 minutes.

C. THE ANALYTICAL MODEL

This model which is a form of the random search model is based on a deterministic detection model. The model has been used in making expected-value calculations of the probability of detection as a function of time for a submarine moving within a sonobuoy field [Ref. 6:pp. 28-29]. It was used in the investigation in order to provide a check on the simulation's structural accuracy.

The performance of each sonobuoy is characterized by an effective detection range which depends on the submarines radiated signal level, the environmental parameters and the searcher's signal processing capability. The sonobuoys are assumed to be systematically distributed throughout the search area such that their coverage is non-overlapping.

The following parameters appear in the model:

Q: effective sonobuoy detection radius.

N: number of sonobuoys in the field.

V: submarine speed.

S: average sonobuoy spacing.

T: search time.

It is assumed that Q is equal to the median detection range or MDR which was obtained from the transmission loss data used in the simulation.

For this thesis $T = 6.56$ hours and is the average time the submarine remains within the sonobuoy field.

The submarine can be detected in two ways: First, it can be detected at the beginning of the search if its initial position is such that it is within the detection range of one of the sonobuoys. Second, it can be detected if the submarine's initial position is such that it is outside the detection range of all the sonobuoys but subsequently it moves into detection range of one of the sonobuoys. This leads to the following expression for the probability of detection [Ref. 6:pp. 28-29]:

$$P_d = 1 - ((1 - \pi(Q^2/S^2))e^{-((2QVT)/(S^2(1 - \pi(Q^2/S^2))))}).$$

III. RESULTS

This chapter presents the results obtained from Model A, Model B and the analytical model. Each of the simulations was done using FOM values of 55 dB, 60 dB, 65 dB and 70 dB. The results of the simulations were then compared with the results obtained using the analytical model. In Model A, a sensitivity analysis was done of the three standard deviation terms of the random variables X_1 , $X_2(t)$, and X_3 , to determine their effect on P_d .

Probability of detection for an encounter between the submarine and the sonobuoy field was estimated using the statistic:

$$(6) \quad \hat{P}_d = \frac{\text{number of detections}}{\text{replications}} .$$

One hundred replications were used. Ideally, a larger number of replications would have been used in order to obtain a higher degree of statistical validity. However, one hundred replications is a compromise that was made in order to limit computer processing time. Pseudorandom numbers were generated using the LLRANDOMII package as installed on the IBM 3033 at the Naval Postgraduate School [Ref. 7].

Figures 3.1 through 3.4 provide a graphical comparison of the probability of detection as a function of the number of sonobuoys for each of the models. The data corresponding to these curves is summarized in Tables 3.1 to 3.4. The values used for σ_L , σ_S , and σ_E in Model A were 4.6

dB, 4.6 dB and 4.6 dB respectively, corresponding to a standard deviation of 8 dB for $X(t)$. For Model B the standard deviation of $X(t)$ was 8 dB.

A sensitivity analysis was performed on the three standard deviation terms and the results are graphically presented in Figure 3.5 with the corresponding data in table 3.5. Figure 3.5 was generated by running Model A, using four combinations of the three standard deviation terms at an FOM of 60 dB. For three of the combinations, each standard deviation term, σ_L , σ_S and σ_B designated as L, S and B in the graph, was set at 7.0 dB while the remaining two were set at 2.7 dB. The fourth case had the three standard deviation terms equal to 4.6 dB.

Smoothed curves were superimposed over the data generated by the two simulation models, in order to gain a better impression of the pattern of dependence of P_d on the number of sonobuoys. A procedure known as locally weighted regression or LOWESS was used to generate the smoothed curves [Ref. 8:pp. 94-104].

An inspection of Figures 3.1 through 3.4 indicates that there were differences between the three models. The relationships between the three curves seem to be independent of FOM. As FOM decreases the number of sonobuoys required to obtain a given probability of detection increases, for all three models. The curve generated by the analytical model lies between the two curves generated by Model A and Model B and the curve generated by Model B lies well above the curve generated by Model A, for all values of FOM.

The difference between Model A and Model B is in the way they model the stochastic component of signal excess and this difference affected the

estimate of the required number of sonobuoys to gain a detection with a given probability. The curve generated by Model B which corresponds to a lambda-sigma jump signal excess fluctuation process lies well above the curve generated by Model A. So, for example in estimating the number of sonobuoys required to obtain a 50 % probability of detection of the submarine at an FOM of 55 dB, Model B estimates it would take approximately 75 sonobuoys, Model A 150 sonobuoys and the analytical model 125 sonobuoys.

An inspection of Figure 3.5 indicates that changing the values of the standard deviation terms causes an effect on the simulation models estimation of the number of buoys required to gain a detection with a given probability. The curves start out fairly close together and then separate as the number of sonobuoys increase. The curve generated by the case when the long term fluctuation term was dominant lies below the curves generated by the other three cases as the number of sonobuoys increase past 100.

To determine if changing the values of the standard deviation terms had a statistically significant effect on the estimate of the number of sonobuoys required to gain a detection, a contingency table was used and Appendix D presents a discussion of this method. The conclusion using the contingency table was that there was a dependence between the probability of detection and the three standard deviation terms, σ_L , σ_S and σ_B .

Finally, a few comments should be made concerning the results. For this scenario it seems the analytical model might be as capable and certainly less costly with respect to the two simulation models in estimating the number of sonobuoys required to gain a detection. Model B consistently produced higher values of P_d than Model A. This could be due to the fact that with Model B there is greater independence between successive values of $X(t)$ whereas with Model A that is not the case. As the independence between successive values of $X(t)$ increases so should the probability of detection.

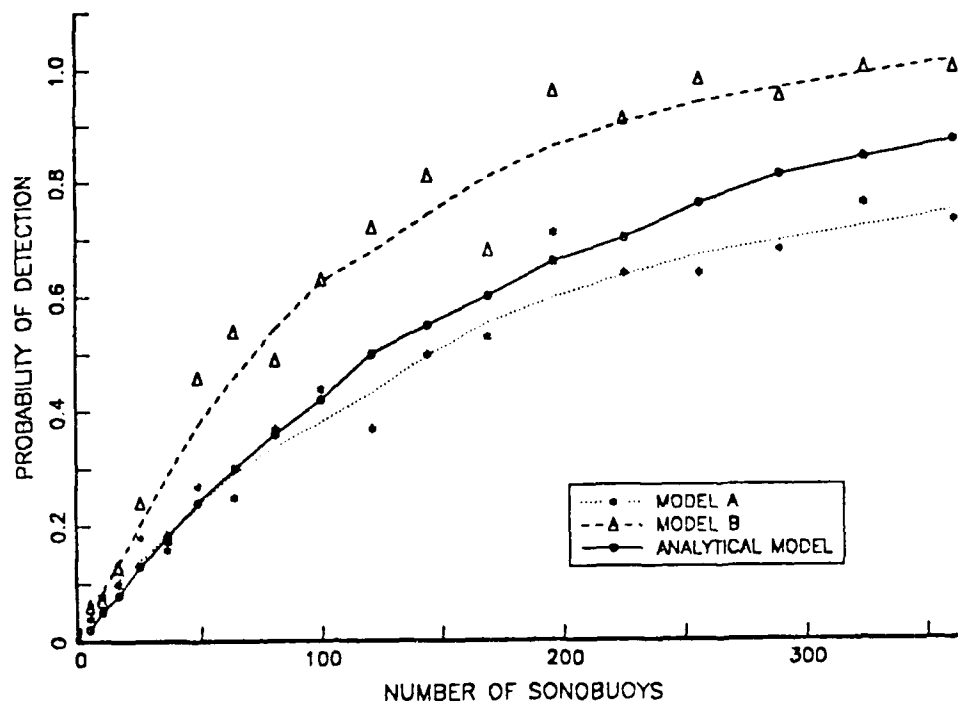


Figure 3.1: Probability of Detection vs. Number of Sonobuoys
for a Figure of Merit of 55

Table 3.1: Probability of Detection vs. Number of Sonobuoys
for a Figure of Merit of 55

Number of Sonobuoys	Probability of Detection		
	Analytical	Model A	Model B
4	0.02	0.04	0.06
9	0.05	0.08	0.07
16	0.08	0.10	0.13
25	0.13	0.18	0.24
36	0.18	0.16	0.18
49	0.24	0.27	0.46
64	0.30	0.25	0.54
81	0.36	0.37	0.49
100	0.42	0.44	0.63
121	0.50	0.37	0.72
144	0.55	0.50	0.81
169	0.61	0.53	0.68
196	0.66	0.71	0.96
225	0.71	0.64	0.91
256	0.76	0.64	0.98
289	0.81	0.68	0.95
324	0.84	0.76	1.00
361	0.87	0.73	1.00

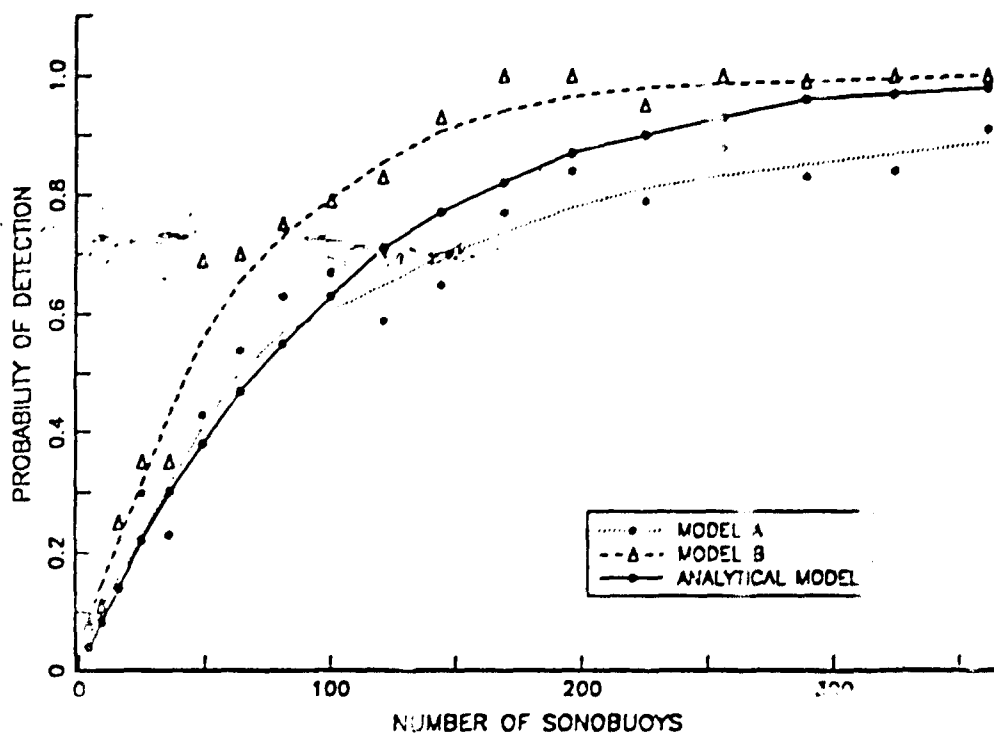


Figure 3.2: Probability of Detection vs. Number of Sonobuoys
for a Figure of Merit of 60

Table 3.2: Probability of Detection vs. Number of Sonobuoys
for a Figure of Merit of 60

Number of Sonobuoys	Probability of Detection		
	Analytical	Model A	Model B
4	0.04	0.08	0.08
9	0.08	0.09	0.11
16	0.14	0.14	0.25
25	0.22	0.30	0.35
36	0.30	0.23	0.35
49	0.33	0.43	0.69
64	0.47	0.54	0.70
81	0.55	0.63	0.75
100	0.63	0.67	0.79
121	0.71	0.59	0.83
144	0.77	0.65	0.93
169	0.82	0.77	1.00
196	0.87	0.84	1.00
225	0.90	0.79	0.95
256	0.93	0.88	1.00
289	0.96	0.83	0.99
324	0.97	0.84	1.00
361	0.98	0.91	1.00

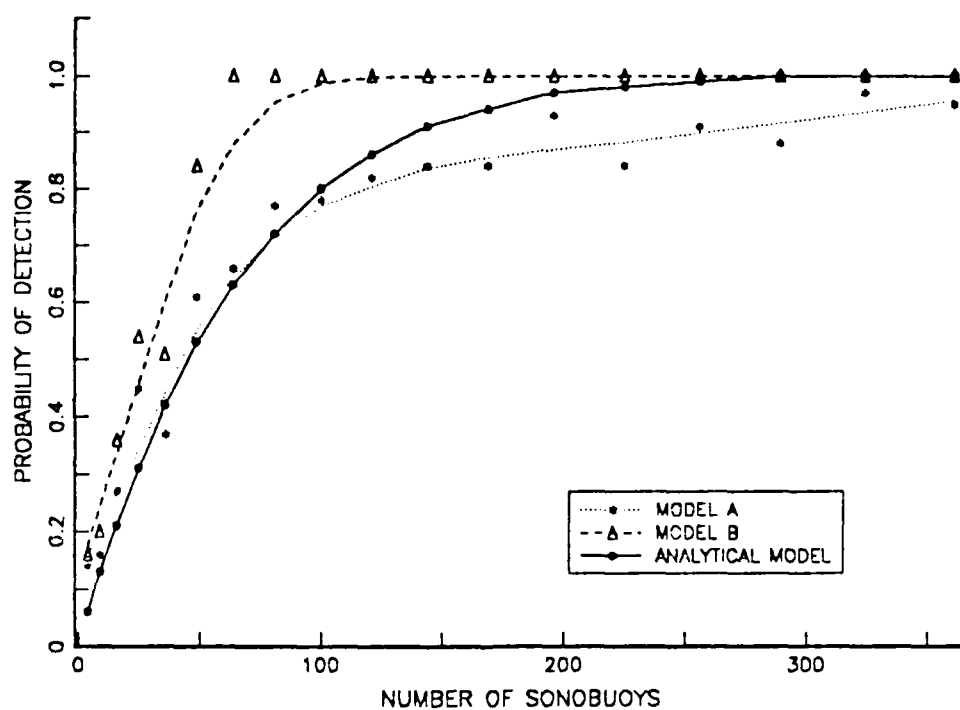


Figure 3.3: Probability of Detection vs. Number of Sonobuoys for a Figure of Merit of 65

Table 3.3: Probability of Detection vs. Number of Sonobuoys
for a Figure of Merit of 65

Number of Sonobuoys	Probability of Detection		
	Analytical	Model A	Model B
4	0.06	0.14	0.16
9	0.13	0.16	0.20
16	0.21	0.27	0.36
25	0.31	0.45	0.54
36	0.42	0.37	0.51
49	0.53	0.61	0.84
64	0.63	0.66	1.00
81	0.72	0.77	1.00
100	0.80	0.78	1.00
121	0.86	0.82	1.00
144	0.91	0.84	1.00
169	0.94	0.84	1.00
196	0.97	0.93	1.00
225	0.98	0.84	1.00
256	0.99	0.91	1.00
289	1.00	0.88	1.00
324	1.00	0.97	1.00
361	1.00	0.99	1.00

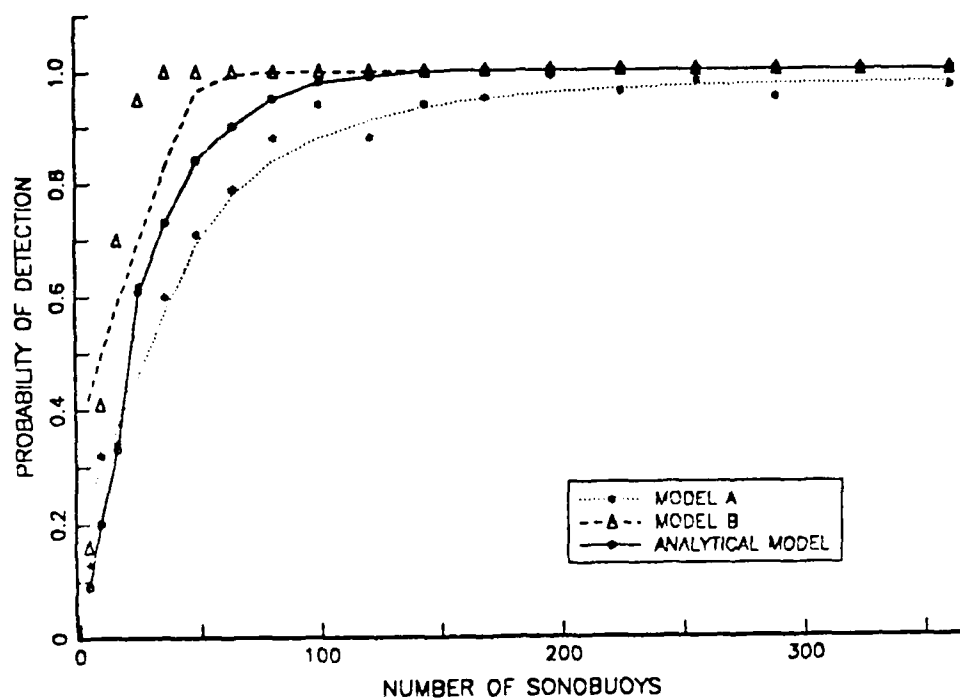


Figure 3.4: Probability of Detection vs. Number of Sonobuoys for a Figure of Merit of 70

Table 3.4: Probability of Detection vs. Number of Sonobuoys
for a Figure of Merit of 70

Number of Sonobuoys	Probability of Detection		
	Analytical	Model A	Model B
4	0.09	0.13	0.16
9	0.20	0.32	0.41
16	0.33	0.34	0.70
25	0.48	0.62	0.95
36	0.61	0.60	1.00
49	0.73	0.71	1.00
64	0.84	0.79	1.00
81	0.90	0.88	1.00
100	0.95	0.94	1.00
121	0.98	0.88	1.00
144	0.99	0.94	1.00
169	1.00	0.95	1.00
196	1.00	0.99	1.00
225	1.00	0.96	1.00
256	1.00	0.98	1.00
289	1.00	0.95	1.00
324	1.00	1.00	1.00
361	1.00	0.97	1.00

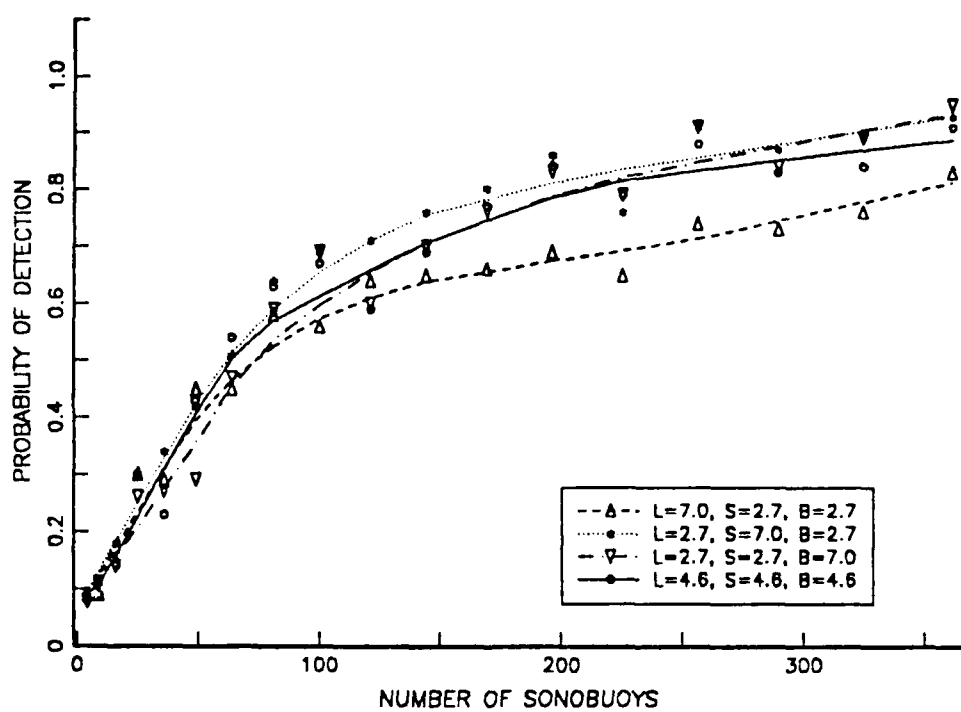


Figure 3.5: Probability of Detection vs. Number of Sonobuoys
Sensitivity Analysis for a Figure of Merit 60. L, S, and B,
represent σ_L , σ_S , and σ_B respectively

Table 3.5: Probability of Detection vs. Number of Sonobuoys
Sensitivity Analysis for a Figure of Merit of 60

Number of Sonobuoys	Probability of Detection			
	$\sigma_L = 7.0$	$\sigma_L = 2.7$	$\sigma_L = 2.7$	$\sigma_L = 4.6$
	$\sigma_S = 2.7$	$\sigma_S = 7.0$	$\sigma_S = 2.7$	$\sigma_S = 4.6$
	$\sigma_B = 2.7$	$\sigma_B = 2.7$	$\sigma_B = 7.0$	$\sigma_B = 4.6$
4	0.09	0.08	0.08	0.08
9	0.09	0.11	0.11	0.09
16	0.15	0.18	0.14	0.14
25	0.30	0.30	0.26	0.30
36	0.29	0.34	0.27	0.23
49	0.45	0.42	0.29	0.43
64	0.45	0.51	0.47	0.54
81	0.58	0.64	0.59	0.63
100	0.56	0.69	0.68	0.57
121	0.64	0.71	0.60	0.59
144	0.65	0.76	0.70	0.69
169	0.66	0.80	0.76	0.77
196	0.69	0.86	0.83	0.84
225	0.65	0.76	0.79	0.79
256	0.74	0.91	0.91	0.88
289	0.73	0.87	0.84	0.83
324	0.76	0.90	0.89	0.84
361	0.83	0.93	0.95	0.91

IV. SUMMARY

The purpose of this thesis is to investigate the effect of using the lambda-sigma jump model in the detection component of APAIR. Two of the models that were used in the investigation are computer simulations. The simulation model referred to as Model A simulates the acoustic detection process similar to the way the Navy's APAIR model does, whereas the simulation model referred to as Model B differs from this in that, in addition, it incorporates a lambda-sigma jump process. The third model that was used is an analytical model called the random search model. This model provided a check on the structural accuracy of the two simulation models.

As the FOM decreases the number of sonobuoys required to detect the submarine increases, for a given probability of detection. This was true for the two simulation models and the analytical model and for every value of FOM investigated, the relationships between the three models remained the same. Model B consistently produced higher probability of detection values for a given number of sonobuoys than did the other two models. Model A however, consistently produced lower probability of detection values and the analytical model produced values falling between the two simulation models, for a given number of sonobuoys.

The differences in the data generated by Model A and Model B were graphically significant. This indicates that the way Model A simulates signal excess fluctuation affects the model's estimate of the number of

sonobuoys needed for a given probability of detection. The estimate of the number of sonobuoys needed for a given probability of detection using Model B, the lambda-sigma jump process model, was consistently less than the estimate obtained using Model A.

In Model A, changing the values of the three standard deviation terms, σ_L , σ_S and σ_B , significantly affected the models estimate of the number of sonobuoys required to gain a detection for a given probability.

Finally in closing, for this scenario it seems the analytical model might be as capable and certainly less costly with respect to the two simulation models in estimating the number of sonobuoys required to gain a detection. Model B consistently produced higher values of P_d than Model A. This could be due to the fact that with Model B there is greater independence between successive values of $X(t)$ whereas with Model A that is not the case. As the independence between successive values of $X(t)$ increases so should the probability of detection.

APPENDIX A: THE SONAR EQUATION

One of the basic forms for the passive sonar equation is:

$$(A.1) \quad SE = 10 \log(S/N) - RD$$

where:

$$(A.2) \quad 10 \log(S/N) = SL - TL - (AN - DI)$$

and:

SL = source level

TL = transmission loss

AN = ambient noise

DI = directivity index

RD = recognition differential

SE = signal excess

The unit of measure for the terms in the sonar equation is the decibel (dB).

As can be seen from Equation A.1, signal excess depends on the following factors: source level; transmission loss; ambient noise; directivity index; and recognition differential. Source level is a measure of the amount of acoustic power that is radiated by a signal. Transmission loss is a measure of the energy loss that occurs when the sound travels from the source to the receiver. Ambient noise refers to all the acoustic energy that is received by a receiver that is in the ocean environment that is not part of the signal. Directivity index is a measure of how well the receiver can discriminate against noise arriving from directions other than that of the signal source. Recognition

differential is the signal-to-noise ratio in decibels at which the operator will detect the signal 50 percent of the time at some specified false alarm rate. In other words, it is the effectiveness of the sonar operator and the sonar equipment in detecting the signal. Signal excess is the difference between the signal-to-noise ratio in decibels and the recognition differential as seen in equation A.1. Frequency of merit, FOM, is defined as follows:

$$(A.3) \quad SE = FOM - TL.$$

It is the transmission loss for which the signal-to-noise ratio in decibels is equal to the recognition differential. FOM is used with transmission loss curves in estimating sonar performance.

APPENDIX B: SENSITIVITY ANALYSIS

To statistically determine if the values of σ_L , σ_S and σ_B have an effect on the probability of detection, an analysis of independence was done using a contingency table [Ref. 9:pp. 323-332]. The data used for this analysis, which is presented in Table B.1, was generated using Model A with the number of sonobuoys equal to 100 and an FOM equal to 70 dB. The contingency table is presented in Table B.2 and the X^2 statistic generated from this data is 118.6802 with 3 degrees of freedom. The results indicate that at $\alpha = 0.05$ the null hypothesis, which is the probability of detection is independent of the values used for the standard deviation terms, cannot be accepted.

Table B.1: Probability of Detection vs. Number of Sonobuoys
Sensitivity Analysis with the Number of Sonobuoys = 100
and FOM = 70

Simulation Run Number	Probability of Detection			
	$\sigma_L = 7.0$	$\sigma_L = 2.7$	$\sigma_L = 2.7$	$\sigma_L = 4.6$
	$\sigma_S = 2.7$	$\sigma_S = 7.0$	$\sigma_S = 2.7$	$\sigma_S = 4.6$
	$\sigma_B = 2.7$	$\sigma_B = 2.7$	$\sigma_B = 7.0$	$\sigma_B = 4.6$
1	0.84	0.93	0.93	0.86
2	0.79	0.92	0.87	0.87
3	0.84	0.93	0.88	0.86
4	0.88	0.90	0.87	0.88
5	0.89	0.92	0.92	0.92
6	0.81	0.95	0.87	0.85
7	0.79	0.89	0.93	0.85
8	0.86	0.91	0.91	0.88
9	0.87	0.91	0.91	0.91
10	0.81	0.83	0.85	0.86

Table B.2: Contingency Table of Probability of Detection with
Number of Sonobuoys = 100 and FOM = 70

	$\sigma_L = 7.0$	$\sigma_L = 2.7$	$\sigma_L = 2.7$	$\sigma_L = 4.6$
	$\sigma_S = 2.7$	$\sigma_S = 7.0$	$\sigma_S = 2.7$	$\sigma_S = 4.6$
	$\sigma_B = 2.7$	$\sigma_B = 2.7$	$\sigma_B = 7.0$	$\sigma_B = 4.6$
P_d	838	909	894	874
$1 - P_d$	162	091	106	126

APPENDIX C: PROGRAM LISTING

```
*****
* This program computes the probability of detection of a      *
* sonobuoy field against a single submarine.                  *
*****
```

PROGRAM DETECT

```
REAL NTLV, SUBSPD, VSPD, XBNDRY, YBNDRY, XDAT, YDAT,
+ STDV1, STDV2, STDV3, SUBH, VARSH, SCALE, X1(1),
+ SSL(1,15), AN(1), RD(1), DI(1), X2(1), X3(361),
+ BLIFE(361), TL(1,20), TBUOY(361), SUM(361,1,361), PV3(3,3),
+ XBUOY(361), YBUOY(361), DEC(6), XSUB, YSUB, TLINT,
+ SHEAD, TIME, F, DIST, SBSPD, RSUB, SSD, SLD,
+ SD, TLOSS, SPL, SPD, SQ, C, DSUB, DEGRAD, SL(361),
+ FS1, RI, SP1, FOM, ISL, PDET, SAMPLE,
+ RAND1(1), RAND3(1), RAND4(1), RAND5(1)

INTEGER I, J, K, L, M, N, LAMB, INTVL, IS1, IS2, IPRINT, NIVET, IMAX,
+ ILINE(361,1), IFLAG, FSL, ISD1, ISD2, ISP1, ISP2, IBY, IDUM, NI,
+ MAXINT, IDET, IZERO, NLINE, NFREQ, NREPS, NBUOY, ITER, ISTEP,
+ IC, ITIME, IDEL
```

C INITIALIZE VARIABLES.

```
DATA DSEED/123456713/
IDET =0
DEGRAD =3.14159/180.
J =1
IZERO =0
```

C READ IN DATA.

```
READ(50,*) NLINE, NFREQ, NREPS, ITIME, IDEL, SAMPLE, NTLV, TLINT
READ(50,*) SUBSPD, SCALE, XBNDRY, YBNDRY, ISEED, XDAT, YDAT
READ(50,*) STDV1, STDV2, STDV3, MAXINT, IPRINT, VSPD
READ(50,*) SUBH, VARSH, IMAX
READ(50,*) ((SSL(I,J), J=1,15), I=1, NFREQ)
READ(50,*) (AN(J), J=1, NFREQ), (RD(J), J=1, NFREQ),
+ (DI(J), J=1, NFREQ)
READ(50,*) (DEC(J), J=1, 6)
READ(50,*) ((TL(I,J), J=1, NTLV), I=1, NFREQ)
```

C CALCULATE AND OUTPUT FOM.

```
FOM = SSL(1,1) - AN(1) + DI(1) - RD(1)
WRITE (45,290) FOM
```



```

290  FORMAT (2X,'FOM = ',F6.2)
      WRITE(45,300)
300  FORMAT (2X,'NUMBER OF BUOYS',4X,'PROBABILITY OF DETECTION')

```

C LAY IN SONOBUOY FIELD

```

      DO 10 L = 2, IMAX
        NBUOY = L**2
        IDET = 0
        DO 20 I = 1, NBUOY
          DO 30 J = 1, NFREQ
            ILINE(I,J) = 0.0
30          CONTINUE
20        CONTINUE
        SCALE = 2*YBNDRY/L
        DO 40 M = 1, L
          DO 50 N = 1, L
            I = ((M-1)*L+N)
            XBUOY((M-1)*L+N) = (XDAT-XBNDRY-SCALE/2)+SCALE*M
            YBUOY((M-1)*L+N) = (YDAT-YBNDRY-SCALE/2)+SCALE*N
            TBUOY((M-1)*L+N) = 0.0
            BLIFE((M-1)*L+N) = 1500.0
50          CONTINUE
40        CONTINUE
        DO 60 I = 1, NBUOY
          TBUOY(I) = 0.0
60        CONTINUE

```

C INITIALIZE SEED

```

      ISEED=ISEED + DSEED

```

C PERFORM SIMULATION FOR THE NUMBER OF REPLICATIONS INDICATED

```

      DO 70 ITER=1, NREPS
        WRITE(6,310) ITER
310      FORMAT(' ', 'ITERATION NUM=', I3)

```

C INITIALIZATION OF VARIABLES

```

      INTVL=INT(SAMPLE)
      IS1=1
      IS2=IS1+INTVL
      CALL LRND(7,RAND1(1),1,1)
      SBSPD=SUBSPD+2*(RAND1(1)-0.5)*VSPD
      SLD=-1.0
      DO 80 I =1, NBUOY
        NIVET=0
      DO 80 J =1, NFREQ
        ILINE(I,J)=0
        IFLAG=0

```

```

        PV3(J,1)=ERG(STDY1,ISEED)
        PV3(J,2)=ERG(STDY1,ISEED)
DO 80 K =1,MAXINT
        SUM(I,J,K)=-250
80      CONTINUE
        IF(IPRINT.NE.1) GO TO 500
        WRITE(40,320)
320     FORMAT(' ',//,3X,'ITER',3X,'TIME',2X,'BUOY')
500     CONTINUE

C  FIND LONG TERM GEOGRAPHIC FLUCTUATIONS.

        DO 100 J=1,NFREQ
          X1(J)=ERG(STDV1,ISEED)
100     CONTINUE

C  FIND SONOBUOY PERFORMANCE.

        DO 110 I=1,NBUOY
          X3(I)=ERG(STDV3,ISEED)
110     CONTINUE

C  GENERATE SUBMARINE LOCATION AND HEADING.

        CALL LRND(9,RAND3(1),1,1)
        CALL LRND(3,RAND4(1),1,1)
        CALL LRND(4,RAND5(1),1,1)
        XSUB=XDAT+2.0*(RAND3(1)-0.5)*XBNDRY
        YSUB=YDAT+2.0*(RAND4(1)-0.5)*YBNDRY
        SHEAD=(2*VARSH*(RAND5(1)-0.5)+SUBH)*DEGRAD
        IF (IPRINT.NE.1) GO TO 520
        WRITE(40,330) XSUB,YSUB,SHEAD,SBSPD
330     FORMAT(4(4X,F6.2))

C  FOR EACH REPLICATION IN THE SIMULATION, TIME STEP THROUGH THE
C  'ENCOUNTER'.  THE TIME STEPS, OR THE SAMPLING INTERVALS, ARE
C  TIMES WHEN SIGNAL EXCESS IS COMPUTED FOR EACH SONOBUOY, TO
C  DETERMINE IF A DETECTION HAS OCCURRED.

520     DO 120 ISTEP=1,ITIME,IDEL

C  FIND SHORT TERM ENGAGEMENT FLUCTUATIONS.

        TIME=FLOAT(ISTEP)
        DO 130 J=1,NFREQ
          IF(ISTEP.LT.IS2) GO TO 530
          IF(J.LT.NFREQ) GO TO 540
          IS1=IS2
          IS2=IS2+INTVL
540     PV3(J,1)=PV3(J,2)
          PV3(J,2)=ERG(STDY1,ISEED)

```

```

530      FS1=IS1
      IF(SAMPLE.EQ.0) WRITE(6,*) 'ERROR SAMPLE'
      F=(TIME-FS1)/SAMPLE
      X2(J)=(1.0-F)*PV3(J,1)+F*PV3(J,2)
130      CONTINUE

C   DETERMINE NEW SUBMARINE LOCATION AFTER TIME STEP INCREMENT.

      DIST=(SBSPD/60.)*IDEL
      XSUB=XSUB+(DIST*SIN(SHEAD))
      YSUB=YSUB+(DIST*COS(SHEAD))

C   COMPUTE THE TRANSMISSION LOSS FOR EACH SONOBUOY.

      DO 140 I=1,NBUOY
      IF(TIME.LT.TBUOY(I)) GO TO 140
      IF(TIME.GT.TBUOY(I)+BLIFE(I)) GO TO 140
      RSUB=SQRT((XSUB-XBUOY(I))**2+(YSUB-YBUOY(I))**2)
      IF(TLINT.EQ.0) WRITE(6,*) 'ERROR TLINT'
      SSD=RSUB/TLINT
      ISD1=INT(SSD)

C   DETERMINE IF THE SUBMARINE IS OUT OF RANGE OF THE TRANSMISSION
C   LOSS VALUES.

      IF(ISD1.GE.NTLV) GO TO 140
      SD=SSD-FLOAT(ISD1)
      ISD2=ISD1+1
      IF(ISD1.EQ.0) ISD1=1
      NIVET=0

C   PERFORM COMPUTATIONS FOR EACH FREQUENCY.

      DO 150 J=1,NFREQ
      TLOSS=(TL(J,ISD2)-TL(J,ISD1))*SD+TL(J,ISD1)

C   COMPUTE SOURCE LEVEL.

      SP1=SBSPD/2.0
      ISP1=INT(SP1)
      ISP2=ISP1+1
      SPD=SP1-FLOAT(ISP1)
      SL(J)=(SSL(J,ISP2)-SSL(J,ISP1))*SPD+SSL(J,ISP1)
      SLD=SBSPD

C   COMPUTE SIGNAL EXCESS.

      SQ=SL(J)-AN(J)-TLOSS-RD(J)+DI(J)+X1(J)+X2(J)+X3(I)

```

C INTEGRATE SIGNAL EXCESS.

```
IF(SQ.LT.0.0) GO TO 550
IF(ILINE(I,J).EQ.J) GO TO 150
IBY=ISTEP-INT(TBUOY(I))+1
IDUM=MINO(IBY,MAXINT)
IF(IDUM.LT.2) GO TO 560
DO 160 K=2,IDUM
  C=FLOAT(K)
  IF(C.EQ.0) WRITE(6,*) 'ERROR C'
  SUM(I,J,K)=((C-1.0)*SUM(I,J,K-1)+SQ)/C
160  CONTINUE
560  SUM(I,J,1)=SQ
  IFLAG=ILINE(I,J)
```

C DETERMINE IF SUBMARINE IS DETECTED.

```
DO 170 K=1,IDUM
  IF(SUM(I,J,K).GE.DEC(K)) ILINE(I,J)=J
  FOM = SQ + TLOSS
170  CONTINUE
  IF(ILINE(I,J).EQ.J) GO TO 570
  GO TO 140
570  CONTINUE
  NI=+I
  IF(IFLAG.EQ.0.AND.IPRINT.EQ.1)
    + WRITE(40,340)ITER,ISTEP,NI
  IF (IPRINT.EQ.1) WRITE (40,350)FOM
350  FORMAT(2X,'FIGURE OF MERIT = ',F25.9)
  IFLAG=ILINE(I,J)
  DO 180 K=1,NFREQ
    NIVET=NIVET+ILINE(I,K)/K
180  CONTINUE
  IF(NIVET.EQ.NLINE) GO TO 580
  GO TO 140
```

C IF THE FREQUENCY WHICH WAS LOST WAS HELD BY THAT BUOY CALL
C 'LOST CONTACT' ON THAT BUOY.

```
550  IF(ILINE(I,J).NE.J) GO TO 590
  NI=-I
  IF(IPRINT.EQ.1) WRITE(40,340) ITER,ISTEP,NI
```

C DECREASE THE NUMBER OF LINES HOLDING CONTACT BY THAT BUOY BY
C ONE.

```
  NIVET=NIVET-1
  IFLAG=0
590  CONTINUE
  ILINE(I,J)=0
150  CONTINUE
```

140 CONTINUE

C CONVERT SUBMARINE HEADING INTO DEGREES.

```
          DSUB=SHEAD*(180./3.14159)
          IF(IPRINT.NE.1) GO TO 120
          IF(ISTEP.GE.600) GO TO 120
          IF(ISTEP.EQ.IS1)WRITE(40,340)ITER,ISTEP,NI,
120      +   RSUB,XSUB,YSUB,DSUB
          CONTINUE
          GO TO 600
```

C COMPUTE RANGE OF THE SUBMARINE TO THE SONOBUOY.

```
580      RSUB=SQRT((XSUB-XBUOY(I))**2+(YSUB-YBUOY(I))**2)
          TIME=FLOAT(ISTEP)
```

C OUTPUT SUBMARINE SPEED, POSITION, AND HEADING.

```
          IF(IPRINT.EQ.1) WRITE(40,360) SBSPD,XSUB,YSUB,DSUB
360      FORMAT(' ', 'SUBMARINE SPEED=', F4.1, 2X, 'XSUB=',
+   F9.2, 2X, 'YSUB=', F6.2, 2X, 'DSUB=', F6.2)
```

C OUTPUT RANGE OF SUBMARINE TO SONOBUOY.

```
          IF (IPRINT.EQ.1) WRITE (40,370) RSUB
370      FORMAT(' ', 'DISTANCE BUOY TO SUB=', F5.2)
```

C OUTPUT TIME OF DETECTION.

```
          IF (IPRINT.EQ.1) WRITE (60,380) ISTEP
380      FORMAT(' ', 'DETECTION AT TIME=', I3)
          IDET=IDET+1
600      CONTINUE
70       CONTINUE
          IF(NREPS.LE.0) GO TO 610
```

C COMPUTE AND OUTPUT PROBABILITY OF DETECTION FOR THE
C CORRESPONDING SONOBUOY FIELD SIZE.

```
          PDET=FLOAT(IDET)/FLOAT(NREPS)
610      CONTINUE
          WRITE(45,390) NBUOY,PDET
390      FORMAT(9X, I3, 20X, F6.3)
340      FORMAT(' ', I4, 4X, I4, 3X, I3, 4X, F6.2, 6X, F6.2, 5X, F6.2, 4X, F6.2)
10      CONTINUE
          STOP
          END
```

C THIS FUNCTION COMPUTES A STANDARD NORMAL RANDOM VARIATE.

```
      FUNCTION ERG(SIG, ISEED)
      INTEGER L1
      REAL SUM, SIG, RAND6(1)
      SUM=0
      DO 700 L1=1,6
        CALL LRND (ISEED, RAND6(1), 1, 1)
        SUM=SUM+RAND6(1)
700   CONTINUE
      ERG=1.41421*SIG*(SUM-3)
      RETURN
      END
```

APPENDIX D: KEY VARIABLES

Key variables of the FORTRAN program.

AN(j) = ambient noise (dB)
BLIFE(i) = sonobuoy life (minutes)
DEC(j) = signal excess decrements (dB)
DI(j) = directivity index (dB)
IDEL = signal excess sampling interval (minutes)
IPRINT = print output option
ISEED = random number initial seed
ITIME = simulation time (minutes)
MAXINT = maximum number of samples per integration period (minutes)
NBUOY = number of sonobuoys
NFREQ = number of frequencies
NLINE = number of frequencies required for detection
NREPS = number of replications
NTLV = number of transmission loss values
RD(j) = recognition differential (dB)
SAMPLE = interval for making random draws of short term fluctuation (minutes)
SCALE = scale factor for sonobuoy position
SSL(i,j) = submarine source level (dB)
STDV1 = standard deviation of long term fluctuation (dB)
STDV2 = standard deviation of short term fluctuation (dB)

STDV3 = standard deviation of buoy to buoy fluctuation (dB)
 SUBSPD = submarine speed (knots)
 SUBH = submarine heading (degrees)
 TBUOY = sonobuoy activation time (minutes)
 TL(i,j) = transmission loss (dB)
 TLINT = transmission loss interval (nautical miles)
 X1(j) = long term fluctuation (dB)
 X2(j) = short term fluctuation (dB)
 X3(i) = buoy to buoy fluctuation (dB)
 XBNDRY = x coordinate of spa boundary
 XBUOY(i) = x coordinate of sonobuoy
 XDAT = x coordinate of datum
 YBNDRY = y coordinate of spa boundary
 YBUOY(i) = y coordinate of sonobuoy
 YDAT = y coordinate of datum
 VARSH = standard deviation of submarine heading (degrees)

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Department of Mathematics
United States Naval Academy
Annapolis, MD 21412 | 1 |
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Surface Warfare Development Group
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Washington D.C. 20375 | 1 |
| 11. | Center for Naval Analysis
4401 Ford Avenue
P. O. Box 16268
Alexandria, VA 22302-0268 | 1 |

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| 12. | John Hopkins Applied Physics Laboratory
Naval Warfare Analysis Department
Attn: R. E. Gingras
John Hopkins Road
Laurel, MD 20707 | 2 |
| 13. | LT Craig W. Goodman
6115 Bison Court
Waldorf, MD 20603 | 3 |
| 14. | R. N. Forrest, Code 55Fo
Department of Operations Research
Naval Postgraduate School
Monterey, CA 93943-5000 | 3 |